

Satellite Soil Moisture Observations: Applications in the UK and India

Report of Pump Priming Project

December 2019



INDIA-UK
Water Centre
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जल केन्द्र

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The India-UK Water Centre promotes cooperation and collaboration between the complementary priorities of NERC-MoES water security research.

भारत-ब्रिटेन जल केंद्र एमओईएस-एनईसीआरसी(यूके) जल सुरक्षा अनुसंधान के पूरक प्राथमिकताओं के बीच सहयोग और सहयोग को बढ़ावा देने के लिए करना है

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Executive Summary

Soil moisture is a critical parameter for understanding the Earth system and in recent years there has been a proliferation of satellite-based soil moisture products. This report investigates current and potential future applications of satellite soil moisture data, with a focus on applications in the UK and India. It represents an overview of the activities and outcomes of an India-UK Water Centre Pump Priming Project entitled '*Synergistic utilisation of EO-based soil moisture observations: Applications in the UK and India*' that were led by the UK co-lead. A review of the literature was conducted, as well as, a survey of end-users and a proof-of-concept demonstration on the use of low-cost sensors for validating satellite soil moisture products. The report is intended for India-UK Water Centre members and stakeholders, and anyone with an interest in the use of soil moisture observation from satellites.

1. Activity Leads

The Pump Priming Project ‘Synergistic utilisation of EO-based soil moisture observations: Applications in the UK and India’ was convened by the India-UK Water Centre (IUKWC) and led by the Activity Leads:

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The Pump Priming Project took place from January – November 2018.

2. Project Aims

The India-UK Water Centre is based around five key cross-sectoral themes and aims to deliver a portfolio of activities across these themes. This activity focused on the themes:

- Developing hydro-climate services to support water security.
- Improving freshwater monitoring frameworks and data for research and management.
- Transforming science into catchment management solutions.

The Pump Priming Project aimed to:

1. Review current and future satellite-based soil moisture (SM) products and their existing and potential future applications in the UK and India.
2. Identify barriers, opportunities and user needs for incorporating satellite-based SM products into existing monitoring and forecasting.
3. Evaluate the potential of integrating Earth Observation (EO) SM estimates into land surface model that may help in improving the estimation of soil hydraulic parameters.
4. Evaluate probabilistic estimates of drought indices, as a function of soil water regime
5. Demonstrate the potential for using new and emerging technologies (COSMOS and low-cost sensors) for validation of EO products.

This report focuses on activities led by the UK Activity Lead, Dr Emma Tebbs, at King's College London including a literature review, an end-user survey and a pilot demonstration of low-cost sensors for validating satellite soil moisture products. These activities contributed to aims 1, 2 and 5. The activities led by the University of Delhi were curtailed due to unforeseen circumstances and were not completed.

3. Project Team

The Pump Priming team was made up of staff listed in Table 1.

Table 1. List of Project Team Members

	Name	Institution
UK		
1	Dr Emma Tebbs	King's College London
2	Harriet Wilson	King's College London
3	Dr Mark Mulligan	King's College London
4	Dr Kristofer Chan	King's College London
INDIA		
5	Dr Manika Gupta	University of Delhi
6	Vikrant Maurya	University of Delhi
7	Dr Prashant Srivastava	Banaras Hindu University, Varanasi

4. Activity Structure

The IUKWC workshop “*Enhancing Freshwater Monitoring through Earth Observation*”, University of Stirling, UK, 19th – 21st June 2017, demonstrated that there is already a huge amount of expertise in the science of remote sensing for freshwater monitoring in both the UK and India, but what is comparatively lacking is the application of Earth Observation (EO) technologies and products in an operational context. Potential barriers to uptake included limited ground-truth data for validation, lack of awareness on available products and the need for better training. Hence, this project aimed to investigate barriers and user requirements in more detail and to investigate where EO products can be applied to improve monitoring and forecasting.

This study focused on soil moisture (SM), a major fundamental variable in global hydrological cycles, which has a huge range of potential applications including agricultural drought and flood forecasting, improving irrigation efficiency, risk mapping (e.g. disease, landslides) and integration into land surface models to improve predictions. As part of this Pump Priming Project a review of the current state of knowledge in the application of satellite-based SM products in the UK and India was carried out, providing valuable new information to aid future India-UK collaborations. Following this, a survey of current and potential end-users of satellite soil moisture data was carried out to identify future opportunities and barriers to uptake of EO-based products. This Project also explored the potential for using new technologies (i.e. low-cost sensors) for validating EO products, as an improvement on current sparse *in situ* measurements which fail to adequately represent SM variability. Low-cost weather stations and soil moisture sensors were constructed and deployed in India as a proof-of-concept study. During the field campaign in India, preliminary findings of the study were disseminated to researchers at University of Delhi and the Banaras Hindu University, Varanasi. This was an opportunity to get feedback from current satellite soil moisture users in India, and these discussions have been included into this report. Hence, the Project also facilitated cross-fertilization of ideas between researchers in the UK and India and identified future opportunities for collaboration.

Key findings from the literature review and user survey are summarised in Section 6.1; the full results will be published in a forthcoming journal article. The publications identified in the literature search are included in the reference list at the end of this report and the questions used in the user survey are included in Annex A.

5. Low-Cost Sensors for Validation of Satellite Soil Moisture Products

This section describes a proof-of concept study to demonstrate how low-cost soil moisture sensors could be used to validate EO products, including soil moisture. It outlines the construction and deployment in India of two low-cost weather stations and soil moisture sensors.

A lack of *in situ* soil moisture data for validation is a significant barrier limiting the application of satellite SM products; this was identified in both the literature review and user survey (see Section 6.1). Existing networks for terrestrial observation have contributed greatly to advancing operational applications of satellite soil moisture products, as well as understanding of land surface dynamics in general. Soil moisture, air temperature, precipitation, and humidity are all important variables in land surface modelling and soil moisture estimation. However, sensor networks are costly and have high maintenance requirements, resulting in a lack of data in many parts of the world. Low-cost and low-resource options for ground observation offers huge potential in filling such data gaps and advancing the use of satellite products.

5.1. Low-Cost, Automated and Open-Source Sensor Technology

Low-cost sensors are a growing area of technology, facilitated by the manufacturing of competitive cloned hardware (e.g. Arduino and Raspberry Pi microcontrollers), open source software (e.g. Arduino IDE, and platforms for development and design sharing (e.g. Instructables, Arduino playground). Low-cost sensor technology enables cost-effective monitoring of environments and enables new applications to develop. It allows a much greater density of sensors and makes it affordable for individuals to monitor their own local environments. More advanced sensor implementation examples extent to automated management resulting from sensor readings (e.g. automated irrigation schemes). The performance of low-cost sensors with reference instruments can vary, but in general temperature and moisture sensors are particularly robust (Fisher and Gould, 2012). However, implementation costs involved in construction, deployment and hardware malfunction can be a significant deterrent of low-cost and open-source sensor designs.

One of the key barriers to the uptake of satellite soil moisture products is the lack of in situ data for validation. *In situ* data can be used in combination with satellite products to validate both satellite soil moisture products and modelled soil moisture data, and to improve the accuracy of downscaling and data assimilation. Hence, in this project low-cost sensors were investigated as a potential source of ground data for validating satellite soil moisture products and land surface modelling estimates.

5.2. The FreeStation Initiative

The FreeStation initiative uses open source hardware and software to build and deploy reliable automatic weather stations with the lowest cost and easiest build possible. These are designed to make reliable, detailed and local climate data more accessible in areas that may have little local financial and technical capacity for the collection of such data (www.freestation.org).

The FreeStation project offers open-source designs for building low-cost weather stations for those with little or no experience of electronics or computer coding. The flexible range of FreeStation designs and sensor combinations offers a weather station suitable for many different projects. The materials needed, design and instructions for the FreeStation products are made freely available upon request (<http://www.freestation.org/building>) to users all around the world, who then go on to construct the weather stations themselves. FreeStation users are then encouraged to upload their weather data back into the FreeStation network and thereby contribute to improving the spatial resolution and reducing the geographical bias in global data coverage.

Weather stations can provide a lot of useful observational data and are a necessary requirement for many field work studies. However, weather stations are generally not cheap and often exceed the budget constraints of many small-scale studies. For longer-term or large projects, a cheaper weather station product offers the potential for a high-density network of stations, which might be particularly important for satellite-based studies.

5.3. Building the Low-Cost Sensors

While the focus of this project was on soil moisture, weather stations were built in addition to soil moisture sensors, as these can provide a complementary set of climatic measurements (temperature, precipitation etc.) that can be useful for data assimilation into models. The suite of measurements collected can also be useful for interpreting the soil moisture values and for validating other complementary satellite datasets (e.g. precipitation). However, for some applications stand-alone soil moisture sensors would be sufficient.

The completed FreeStations, as shown in Figure 1, were based on the FreeStation Meso Automatic Weather Station design (version 5.9, <http://www.freestation.org/building>), which measure temperature, humidity, rainfall, wind speed and direction, solar radiation and soil moisture.



Figure 1. Completed FreeStations during the testing period prior to their deployment.

The original plan was for the soil moisture sensor to be integrated into the FreeStation weather station. However, due to technical issues encountered and time limitations, the decision was made to proceed with separate soil moisture sensors using a simple design from the King's College London lab team. The soil moisture sensor design was based on the same electronic components as the FreeStation, using the Arduino Pro Mini 3.3v microcontroller board as the basis of the logger. The soil moisture sensor used was the Vegetronix VH400 soil moisture probe (Figure 2). The probe was chosen because of the reported high accuracy, capacity to be buried and non-corrosive materials. The sensor is programmed to sleep between measurements resulting in a very low battery consumption rate.

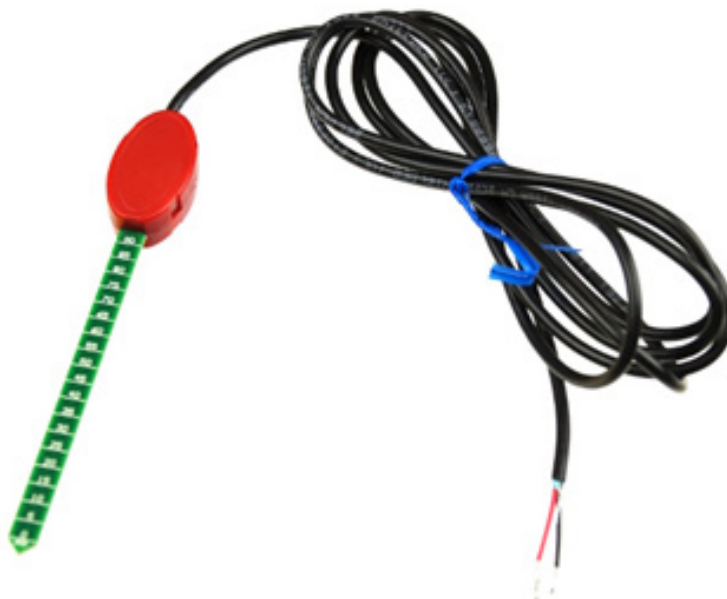


Figure 2. Vegetronix soil moisture probe – VH400

Cost of Materials and Time Considerations

The cost of materials for building the FreeStation Meso Automatic Weather Stations is around £194, including the logger, housing, power supply, and sensors. However, the price of parts can fluctuate considerably.

The build time and any associated labour costs are also an important consideration. In this project the low-cost sensors took significantly longer to build than originally anticipated. This was due to faulty components and time spent waiting for replacement parts to arrive, and troubleshooting. In total, it took three weeks for one person to build the two FreeStations and two days to build and test the soil moisture probes. The soil moisture probes were, therefore, considered much easier to build and source materials for than the weather stations. The build time per station would be significantly reduced if more stations are built as it would become easier to source parts in bulk and easier to construct.

Advice for Building the FreeStations and Other Low-Cost Sensors

This section gives a summary of the lessons learnt during the construction of the FreeStations and soil moisture sensors. Advice is presented for anyone interested in constructing their own low-cost sensors for a research project.

Building sensors as an electronics novice is a steep learning curve. The key challenges encountered when making the sensors for this project were as follows:

- In the beginning, novices may find that they are following instructions without an understanding of how the finished product will work. The instructions take you through the full construction of the weather station; however, upon completion there is a significant chance that the product will not work immediately. It is not until the troubleshooting and installation phase that you will start to make sense of how the product works.
- The first sensor made will be the most difficult and will take much longer than subsequent sensors to make. This must be kept in mind when time planning.
- As the aim is to make a low-cost product, the materials used are also low-cost. This means that faulty parts can be a problem. For example, in this project a whole batch of humidity and temperature sensor parts that we ordered were faulty, causing a significant delay finding the problem and waiting for new parts. In addition, whilst the cost of components is significantly reduced by ordering directly from the manufacturers (often located in China), lead times can exceed a month.
- If a problem is encountered, often the only way for novices to fix it is by trial-and-error. While this can be frustrating, it also helps you to gain a better understanding of the product and puts you in a good position to fix things if they don't work when the sensor is deployed in the field.
- It is tricky to work towards a deadline when building low-cost sensors, as there are often unexpected issues encountered. In this project, the time taken to finish the sensors was increased dramatically by the need to order new parts to replace those that were faulty.

After our experiences building the sensors for this project, we would like to pass on some advice to anyone considering using low-cost sensors:

- Make one complete sensor first. Then make any further sensors once the first one is complete. This can save you time and materials as mistakes are likely to be made with the first of any design. Subsequent sensors can then be built in parallel.
- Order parts early, and order spares. Lead times for low-cost electronics can be very long as they are often shipped from manufacturing countries such as China. There is also a high chance that at least a few parts will be faulty or that during construction of the sensors some parts will get damaged.

- Test the individual sensor parts first. This will prevent you from having to troubleshoot once all the sensors are wired up. Additionally, if you have soldered faulty parts it can be tricky to de-solder the part to replace it.
- See example websites below for checking your sensors work:
 - Soil moisture probes: <http://www.cheapvegetablegardener.com/how-to-use-vegetronix-soil-moisture/>
 - Temperature and humidity sensor: <https://learn.adafruit.com/adafruit-htu21d-f-temperature-humidity-sensor/wiring-and-test>
- Give yourself time to test the sensors. If you can put the finished sensors next to a calibrated weather station, this provides a great opportunity to calibrate your weather stations.

5.4. Fieldwork Summary

A field trip to India was conducted in September 2018 to deploy the low-cost sensors as part of the project deliverables. The main objective of the fieldwork was the installation of the two FreeStations and soil moisture probes at two locations in India. This section will summarise the purpose of the fieldwork, the schedule, the outputs and potential future work.

Fieldwork Aims

Globally there are a number of dense soil moisture sensor networks (e.g. Remedhus in Spain and Tereno in Germany), which have facilitated the use of satellite data for many applications, such as flood modelling. However, there is significant spatial bias in the global distribution of soil moisture sensors and there are significant data gaps in some areas. Increasing the availability of in situ soil moisture data using low-cost sensor networks will improve the usefulness of satellite soil moisture products by enabling better calibration and validation of these products, particularly in areas where in situ data is currently lacking. Hence, one of the project objectives was to ‘*demonstrate the potential for using new and emerging technologies (COSMOS and low-cost sensors) for validation of EO products*’.

To address this objective, existing designs for low-cost sensors were evaluated as a means for collecting data for the validation of satellite projects. The two FreeStation Meso Weather Stations and separate soil moisture sensors were deployed in India, where there are many applications that could be improved by satellite soil moisture products but where there is a general lack of in situ validation data. The data from the FreeStations will also be uploaded to the FreeStation data network to contribute to filling spatial and temporal data gaps.

Fieldwork Schedule

The fieldwork was conducted from the 9th – 18th September 2018, at the end of the monsoon, when the rains had mostly stopped. The sensors were deployed at two locations in India therefore, requiring travel between sites. To allow for travel, deployment, presentations and troubleshooting, 10 days in the field were required. The schedule for the trip is outlined in Table 1.

Table 1. Fieldwork schedule

Date	Location	Tasks
9 th September	Delhi	Travel London to Delhi
10 th September	Delhi	Installation of Freestation & Soil Moisture sensor
11 th September	Delhi	Presentation at Delhi University
12 th September	Delhi/Varanasi	Train to Varanasi
13 th September	Varanasi	Installation of Freestation & Soil Moisture sensor
14 th September	Varanasi	Presentation at Banaras Hindu University

15 th September	Varanasi	Check data & troubleshooting for Freestation
16 th September	Varanasi/Delhi	Train to Delhi
17 th September	Delhi	Check data & troubleshooting for Freestation
18 th September	Delhi/London	Travel Delhi to London

Key Output: Sensor Deployment

Overall, the deployment of the sensors was successful. At both sites, the FreeStations and soil moisture sensors were installed and tested, and found to be successfully logging data. The deployment conditions were different for each site and the location was decided by the site characteristics and the host requirements. The exact situation of the sensors was also a function of available and secure space and poles for fixing the sensor. The environmental set-up for the FreeStations is shown in (Figure 3).



Figure 3. FreeStation meso weather stations at (left) University of Delhi – roof of the Geology Department, and (b) Banaras Hindu University – experiment fields.

At the University of Delhi, the campus was very busy and there was a lack of free space. The FreeStation was therefore positioned on the roof - allowing easy access for maintenance. One potential issue is the effect of high albedo (mosaic floor) on the pyranometer readings. The soil moisture sensor was located on the department lawn. Unfortunately, one probe was broken after a few days of deployment, and this was assumed to be due to it being run over by a lawn mower. This did not prevent further measurements being collected as there were two soil moisture probes for each sensor, however it did highlight the need to find a suitable location for long term deployment, including potentially marking out the area to help protect the sensors. At Banaras Hindu University, both the Freestation and soil moisture sensor were located in the crop experiment site, which is a secured site and unlikely to be disturbed.

While the deployment of the sensors was successful, there were some initial teething issues. At the University of Delhi, the FreeStation initially had some power issues due to an overcharge of energy through the solar panel, causing smoking of the battery holder. This was due to a thicker wire being used from the solar charge regulator than specified in the guidance. This caused some problems and required re-wiring and re-testing of the sensor, however this was eventually

resolved. Although the battery holder continued to work, the batteries were not as tightly fitted, and a new holder may be required. At the Banaras Hindu University there were also some issues resulting from poor connections in the solar regulator. This was also fixed in the field but may cause ongoing problems if the cables continue to come loose. The soil moisture sensors are a simpler design and easier to deploy, however they did have to be reprogrammed on site as they had not been updated to Indian time.

The troubleshooting process required to solve these problems served as a very useful teaching tool for sharing knowledge of the product set-up. Those in India that will be responsible for maintaining the sensors were able to assist with the troubleshooting process and showed a lot of interest and prior knowledge of electronics (see Figure 4). It is likely that any common issues that could arise in the future with the sensors, will be easily resolved by the on-site teams or with assistance over Skype.



Figure 4. Students from the University of Delhi and Banaras Hindu University assisting with the installation of the FreeStations.

Additional Outputs

Beyond sensor deployment, the field trip also contributed to other project objectives. In particular, the field work allowed an opportunity to present and gain feedback on the project results with current satellite soil moisture users in India.

A 20-minute presentation was given at both the University of Delhi and the Banaras Hindu University (Figure 5), on the project findings, followed by around 10 minutes of questions. The presentation included a summary of the literature review, survey and sensor construction. Around 15 university staff and students attended each presentation. These presentations were used to disseminate preliminary results of the project, and to instigate discussions around the topic of satellite soil moisture products.

In general, the field trip offered many opportunities for discussion with both new and experienced satellite soil moisture users in India. This discussion was very important for confirming the findings of the literature review and ensuring nothing important was missed. A few additional sources for the literature review were identified following these discussions.

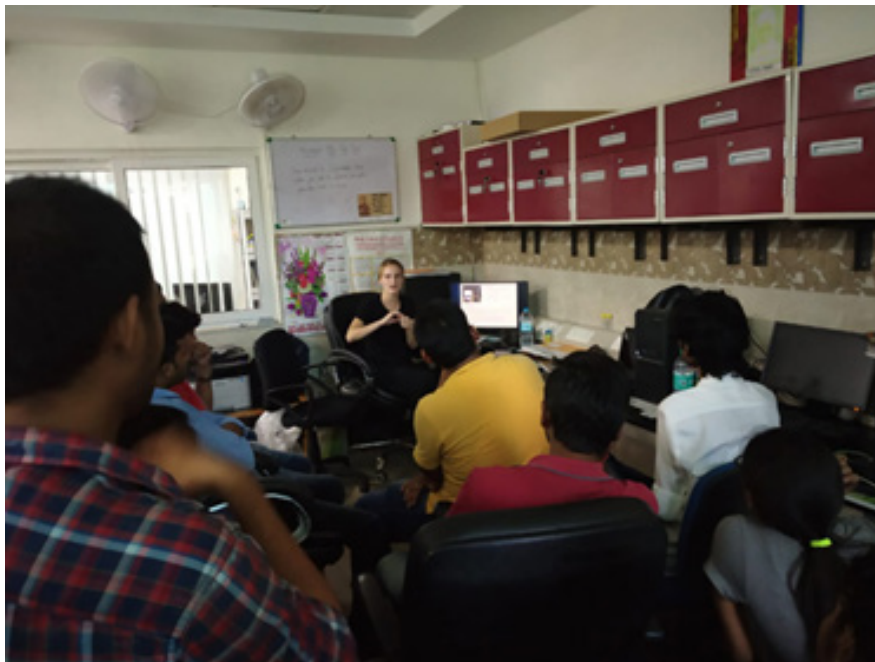


Figure 5. Presentation of project findings at the Banaras Hindu University soil moisture lab

Future Work

The success of the sensor deployment has demonstrated the high potential for future follow-on projects. In particular, the individual soil moisture sensor was shown to be cheap, light and simple to work with. There is interest in deploying more sensors at the Banaras Hindu University, where Dr Prashant Srivastava's lab is interested in exploring the use of in situ sensor networks for validating downscaled satellite soil moisture data for agricultural monitoring (e.g. precision irrigation planning). A greater sensor network would increase the value of the data for validation, and also resolve questions around the sensitivity of the soil moisture sensors to soil types and the accuracy of sensors. This could be a very simple and cost-effective follow-on project which could contribute to the advancement of satellite products in regions where in situ data is a limitation.

Summary

The fieldwork component of this project was highly beneficial to the project aims and has also identified areas for potential future work. The main purpose of the fieldwork was the deployment of the sensors, which was successful although highlighted some of the issues of working with open-source, low-cost technology. The fieldwork also provided the opportunity to share and promote the findings of the project and contributed to identifying additional sources for the literature review. The fieldwork has initiated potential further collaborations with the University of Delhi and Banaras Hindu University, to follow-on with work carried out in the project.

6. Activity Conclusions and Outputs

This section summarises the key findings and outcomes of the literature review and user survey, and the proof-of-concept study on low-cost sensors for validation (section 5). Conclusions and outcomes of the activity are also presented.

6.1. Key Findings and Outcomes

Summary of Findings of the Literature Survey:

Soil moisture (SM) is a critical parameter for understanding the Earth system; it controls the partitioning of water and energy at the Earth's surface and is an important variable influencing plant growth. SM is an important driving variable for many water-related hazards, including flooding, drought, landslides and wildfires.

The last decade has seen a proliferation of EO-based SM products, largely due to advancements in retrieval methods and a rise in the number and capabilities of satellite sensors. The accuracy of satellite SM products has improved, and now satellite products are comparable to SM estimates from land surface models. Nevertheless, difficulties in producing accurate SM retrievals remain, such as radio frequency interference and the influence of background information from soil texture and dense vegetation (Muñoz-Sabater et al., 2016). To overcome the limitations of individual datasets, merged satellite products have been developed such as the ESA Climate Change Initiative SM product, the first global, multi-decadal SM dataset, released in 2012. Synergies between satellite and modelled SM has also been explored as an opportunity to improve accuracies and to manipulate the spatial and temporal resolution of soil moisture datasets (Al-Shrafany et al., 2014; Brocca, 2017a), and increasingly satellite SM products are being incorporated into models through the process of data assimilation.

Satellite-based SM products have huge potential for improving monitoring and forecasting in India and the UK. There are a wide variety of potential applications of satellite SM data but many of these are still in their infancy and have yet to be taken up operationally by governments or commercial organisations. This study reviewed available literature and identified three main application areas for satellite SM products: climate and weather forecasting, environmental hazard monitoring, and agricultural services.

Numerical Weather Prediction (NWP) modelling is regarded as one of the most mature satellite SM applications (Wagner et al., 2013a). In the UK, there are currently two operational NWP models which incorporate satellite soil moisture products, and in recent years, there has been strong collaboration between the UK and India focusing on NWP modelling and prediction of the Indian monsoon (e.g. the INCOMPASS project), and there is potential for incorporating satellite observations of SM variability to help improve monsoon predictions.

The accuracy of NWP modelling in the UK has benefited from the availability of abundant in situ meteorological observations, and more recently observed soil moisture data has also become available, through the Cosmic Ray SM Monitoring Network (COSMOS-UK) deployed in 2013. The COSMOS-India project, a partnership between COSMOS-UK and universities in India, will improve the availability of SM data for India and will contribute to improved understanding of SM dynamics, and the validation/calibration of satellite products. In situ SM data in India is scarce and the availability of open access in situ data will be a huge benefit for studies with a range of different applications.

Satellite SM data has great potential to contribute to regional drought monitoring. Satellite datasets are already widely used to quantify drought severity. However, although soil moisture is the most important variable for agricultural drought, lack of data has often led to the use of purely meteorologically based drought indices (Nicolai-Shaw et al., 2016; Martinez-Fernandez et al., 2016; Mu et al., 2013), which can result in the incorrect parameterization of drought (Halwatura et al., 2017). Hence, satellite SM products can improve the detection of agricultural drought, and multidecadal products such as ESA CCI SM are advancing understanding of long-term trends in drought (Nicolai-Shaw et al., 2017; Rahmani et al., 2016; Chen et al., 2016). The potential for incorporating SM data into national drought monitoring in India is particularly high given the existing use of similar satellite-derived meteorological drought indices. However, the diversity of land cover and climate zones in India presents significant challenges for national-scale application.

Flood forecasting is a well explored application for satellite soil moisture products. However, significant challenges remain for the assimilations of satellite soil moisture data into flood models, including the mismatch in spatial resolution and soil depth between models and satellite products. Several studies have used dual assimilation, including both SM as a state variable and soil moisture corrected-rainfall as a forcing variable (Crow and Ryu, 2008; Chen et al., 2011, 2014; Tekali & Fouli, 2017; Massari et al., 2018). The use of satellite soil moisture products for flood forecasting in India is rare, with one of the main challenges being the poor spatial resolution satellite soil moisture products. Hence, studies in India have focused on the development of downscaling methods to improve the spatial resolution of soil moisture data (Singh et al., 2016). In the UK, there are projects exploring the assimilation of satellite SM data into the JULES land surface model to improve flood prediction (e.g. the SINATRA project).

Satellite SM data has been used for monitoring the crop condition (McNally et al., 2015; Champagne et al., 2016; Yang et al., 2016), and predicting yields (Ines et al., 2013; El Sharif et al., 2015). Advancements in microwave satellite sensors has also shown promise for irrigation monitoring (Kumar et al., 2015; Gupta et al., 2016; Lawston et al., 2017; Singh et al., 2017), however the application is still relatively new (Brocca et al., 2017c; Petropoulos et al., 2018). Agricultural applications present challenges that must be addressed before the use of satellite SM products becomes operational, including: spatial and temporal resolution; penetration depth; and acquisition conditions (heterogeneity of vegetation cover and RFI) (Petropoulos et al., 2018). However, new satellite products provided in near real time and with finer (< 10 km) spatial resolution will help to address some of these issues (e.g. SMAP passive enhanced product, SMOS near real time etc.).

Remote sensing-based crop monitoring and forecasting is well developed in India (Parihar, 2016; Rajak et al., 2016; Jayakumar et al., 2016; Chakraborty et al., 2015), and there is much scope to utilise satellite SM products (Parihar, 2006, Parihar, 2016). Possibilities include incorporating satellite SM products into existing national crop yield modelling or using the data to support decision making, for example by providing SM based information on crop conditions and environmental hazards to farmers via text message (Venkatasubramanian et al., 2014; Chattopadhyay and Chandras, 2018). Satellite SM data has also been used to assess the impact of policy changes in India. For example, Singh et al. (2017) used AMSR-E SM to detect pre- and post- Water Act irrigation estimates. In the UK, there are existing satellite products for commercial crop monitoring (e.g. Land Cover Plus: Crops), and the new Sentinel-1 10 km SM product has potential for enhancing existing crop monitoring services for applications such as crop stress and water use mapping across the growing season.

The main barriers preventing the uptake of satellite SM observations identified in the literature were: availability of ground data, product characteristics such as spatial resolution, data access, training, awareness and collaboration. The significant spatial bias in ground-based SM observations, and the large data gaps in some regions, including India, is limiting the calibration and validation of satellite products. Product and sensor characteristics also present barriers and in particular spatial resolution is still limiting for some applications. Downscaling methods can help to address this, but these can introduce additional uncertainties. The planned high-resolution L-band sensor onboard NISAR, is likely to drive huge advancements, particularly for India (Mohanty et al., 2017). Better characterisation of uncertainty is also required for incorporating satellite products into models. Data access policies can deter potential users and ideally, to maximise the use of satellite products, data should be open source and as simple to access as possible. Many products are already available open source but there is potential for ease of access to be improved. There is a need for more training in the use of satellite SM observation and for more information on available products. Lack of awareness is another key barrier, particularly since advancements in satellite SM detection are relatively new. There is also a need for more collaboration between the remote sensing community and other disciplines to advance the use of satellite soil moisture products in new application areas.

Key Results from the User Survey:

- A self-selecting sample of 88 people were surveyed, made up of 68% from academia and 23% from the private sector, primarily working in India and the UK. Respondents included people from a range of disciplines, working across different climatic zones and habitat types.
- Just under half of respondents (48%) had used satellite SM data before. These current users had made use of many different satellite sensors, the main ones being SMOS and SMAP, and several also mentioned the ESA CCI merged satellite product.
- 86% of current users had used ground data for validation of satellite SM estimates. Some has used existing observation networks, while others collected their own SM data, including setting up new sensor networks. There was a perceived lack of ground data for validation and some had used alternative approaches for validation such as inter-comparison with other satellite datasets and models.
- Out of the 46 respondents who had not used satellite SM data (potential users), 48% had considered using satellite soil moisture products. When asked what satellite sensors they had considered, 31% selected “Don’t know” suggesting a lack of awareness of available products and sensors. The most common sensors that had been considered were SMAP, Sentinel-1 and TRMM-TMI.
- The applications where potential users thought SM data could be most usefully applied were agricultural management, drought monitoring and forecasting, water management, environmental monitoring and land surface modelling.
- 84% of potential users said they were likely to use satellite data in future, for applications including drought monitoring, climate change research, incorporating into models, commercial applications and understanding vegetation dynamics.
- Data requirements varied depending on the application, but the most common requirements were for a spatial resolution of “Less than 1 km”, “Daily” repeat frequency and preferred data formats of NetCDF and GeoTiff. Global coverage was required by most current users, but regional coverage was enough for most potential users. Knowledge of product uncertainties was also mentioned as an important data requirement.
- The key characteristics of satellite SM data for current users were “Accessibility of data”, “Spatial resolution” and “Temporal resolution”, while for potential users the most important characteristics were “Accessibility of data”, “Spatial resolution” and “Spatial coverage”.
- On average, all data characteristics were rated as either “Important”, “Very important” or “Critical” for both current and potential users, highlighting the challenges for data providers to produce products which fulfil the needs of users across many different criteria.
- Current users found “Availability of ground truth data”, “Availability of near real time data” and “Spatial resolution” the most restrictive characteristics, while “Accessibility of data” and “Spatial coverage” were the most beneficial.
- Potential future users were discouraged most by “Cost of data”, “Accessibility of data”, “Cloud penetration” and “Availability of ground truth data”. The most encouraging characteristics were “Spatial coverage”, “Spatial resolution” and “Accuracy of the satellite sensor”. This highlights that there is a need to get the message out to potential users that there is lots of free satellite SM data available, and to provide guidance on how to access available products.
- When asked what improvements in satellite-based soil moisture products would be most advantageous to their application area, by far the most common request was for improved spatial and temporal resolutions. Accuracy and quality of the retrievals also came up as

important, as well as improvements in the quantification of errors and uncertainty. Other required improvements included an ability to retrieve SM under dense vegetation and the sampling of SM in deeper soil layers. Training and data accessibility were also mentioned as important areas.

- When asked ‘How might satellite-based soil moisture data benefit you and your discipline in the future?’ a wide range of discipline and application areas were mentioned including climate change, water resources management, agriculture, land management, drought monitoring, crop productivity, vegetation stress, geohazards, land surface modelling, land-atmosphere interactions and numerical weather prediction. A word cloud generated from the responses to this question can be seen in Figure 6.

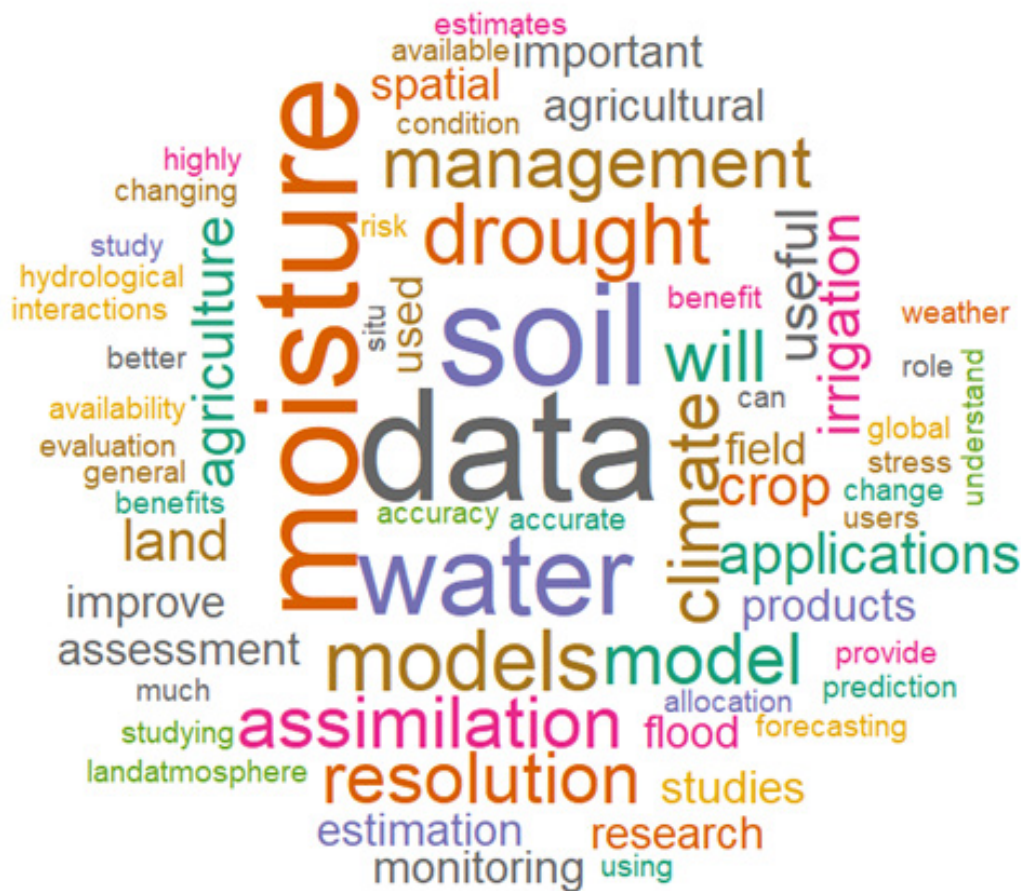


Figure 6. Word cloud generated from the responses to the question ‘How might satellite-based soil moisture data benefit you and your discipline in the future?’

- Respondents identified SM data as being “important”, “required” and even “critical” for their research, with the potential to offer immense benefits across a wide range of disciplines.
- Respondents were asked the extent to which different application areas will benefit from satellite soil moisture data in future. Benefits were expected across all application areas, but the areas identified as having the most potential to benefit were: “Drought monitoring and forecasting”, “Hydrological modelling”, “Water management”, “Agricultural management”, “Land surface modelling” and “Flood monitoring and forecasting”.

- Only 17% of respondents had received training in the use of satellite SM products, but 91% said that they would find future training in satellite soil moisture data products useful. The preferred format for training was a workshop taking place over several days with a mix of practical “hands on” exercises and lectures to cover theoretical aspects. However, some respondents indicated a preference for online training delivery. Topics that should be covered included: data access, data processing, understanding uncertainty, data assimilation and applications.

Summary of Pilot Study and Fieldwork:

Low-cost sensors are a growing area of technology that have potential to contribute the validation of EO data products by increasing the availability and spatial coverage of ground observations. There is also potential for such data to be incorporated into models, e.g. through data assimilation. However, low-cost sensors are not without their limitations. In this study, the feasibility of using low-cost sensors for EO data validation was investigated. Two FreeStation weather stations and two standalone soil moisture loggers were constructed and successfully deployed in India, at University of Delhi and Banaras Hindu University, Varanasi. The individual soil moisture sensors were shown to be cheap, light and simple to work with, and the FreeStations weather stations were also valuable as they can provide a suit of meteorological measurements that can be used for a range of applications. During the field campaign, potential follow on projects were identified, including a collaboration with Banaras Hindu University to deploy a network of low-cost soil moisture for validating downscaled satellite soil moisture data for agricultural monitoring.

Based on our experiences in this study the following conclusions were drawn:

Advantages of low-cost sensors:

- Their low-cost makes them affordable within the budget of small projects and means that larger projects can purchase many sensors to increase spatial coverage.
- Bespoke designs can be developed to incorporate multiple different sensors or for automated logging at time intervals specified by the user.
- Building the sensors is a good way to develop knowledge of electronics, coding and sensor design, and this can be useful for maintaining the sensors in the long-term or for working out how to fix them if things go wrong in the field.

Disadvantages of low-cost sensors:

- The sensors can take a long time to design and build and it can be hard to predict how long they will take to make, particularly for the first few sensors as a lot of time is often spent troubleshooting.
- Reliability of the sensors can be a problem, but this can be improved by time spent developing robust designs.
- Accuracy can also be an issue but in general temperature and moisture sensors are particularly robust (Fisher and Gould, 2012).

Advice for people considering using low-cost sensors:

- Low-cost sensors are a good option when many sensors are required. If only a small number of sensors are needed, then low-cost sensors may not be the best option as time spent learning how to build the sensors and perfecting the designs can be considerable.
- Order parts well in advance as lead times can be well over a month and order spares as parts can often be faulty due to the low-cost nature of the products.
- Test individual components first before soldering to avoid problems later.
- Make sure you factor in time for testing and ideally do a comparison with commercial equipment as a way of calibrating your low-cost sensors.

6.2. Conclusions and Recommendations

Soil moisture is a critical parameter for understanding the Earth system. The last decade has seen a huge increase in the number of EO-based SM sensors and products, and substantial improvements in retrieval methods (Brocca et al., 2017b). Multi-sensors products have been developed (e.g. ESA CCI SM), to overcome the limitations of individual sensors and to provide long-term SM observations. Some difficulties in the retrieval of satellite SM remain, such as radio frequency interference and the influence of dense vegetation (Petropoulos et al., 2015). Additionally, for some applications the coarse spatial resolutions and shallow penetration depths of satellite SM products still present challenges. However, downscaling methods and the assimilation of data into models can help to address some of these difficulties.

A review of the literature demonstrated that satellite-based SM products have huge potential for improving monitoring and forecasting in India and the UK. NWP modelling is one of the most mature satellite SM applications (Wagner et al., 2013a) and in the UK satellite SM observations are used in two operational NWP models. Furthermore, an India-UK collaboration is now exploring the use of satellite SM for improving predictions of the Indian monsoon. Satellite SM data has great potential for monitoring of water-related hazard, such as regional droughts, particularly in India, and flood forecasting. Potential agricultural applications include assessing crop condition, predicting yields and monitoring irrigation. There are opportunities to develop these products into commercial agricultural services or for use in supporting government decision-making.

The user survey carried out in this study identified SM data as being highly important across many different disciplines. The application areas identified as having the most potential to benefit from satellite SM data were: drought monitoring and forecasting; hydrological modelling; water management; agricultural management; land surface modelling; and flood monitoring and forecasting. A wide range of other potential applications were also mentioned including climate change studies, land management, crop productivity, vegetation stress, geohazards, land-atmosphere interactions and NWP.

Despite the clear potential benefits of satellite SM data, several barriers preventing the uptake of satellite SM observations were identified in the literature, including: availability of ground data, spatial resolution, data access and training, and awareness. The user survey also provided information on potential barriers and user requirements. Data accessibility and spatial resolution were identified by users as the most important characteristics of satellite SM products. Spatial coverage was the main positive aspect of current satellite products identified by users, and limiting factors included availability of ground truth data, availability of near-real-time data and spatial resolution.

Of the 46 potential users surveyed, 84% said they were likely to use satellite SM data in future. However, there was a lack of awareness of available satellite sensors amongst potential users and a desire for more knowledge and training. While current users were happy with data accessibility, interestingly potential users identified data cost and accessibility as discouraging. When asked what improvements in satellite-based soil moisture products would be most advantageous, the most common responses were improved spatial and temporal resolutions, accuracy of retrievals and quantification of uncertainty. A large proportion of those surveyed (91%) said that future training on satellite soil moisture products would be useful to them.

Both the literature review and user survey identified a lack of in situ SM data as a key problem limiting the uptake of satellite SM products. In the UK, a network of cosmic ray soil moisture sensors (COSMOS-UK, <https://cosmos.ceh.ac.uk/>) provides in situ observations, and the COSMOS-India project is improving the availability of in situ SM data for India. However, these systems are highly expensive so the number of sensors that can be deployed is limited. In this study, a pilot demonstration was carried out to investigate the feasibility of using low-cost sensors for validating EO products. Weather stations and SM sensors were constructed and deployed in India and these experiences highlighted the practicalities of using low-cost sensors such as the significant time investment required to learn how to build the sensors and develop

robust designs. In future, there is potential for a larger study to establish a network of low-cost SM probes and investigate their use for validating downscaled satellite products.

Recommendations:

This Pump Priming Project has highlighted the huge potential for satellite SM products to contribute to monitoring and forecasting in the UK and India. To increase use of satellite SM data in the UK and India, and take advantages of the benefits and opportunities it offers, the following actions are recommended:

- **Data Access:** Satellite SM data should be easily accessible. It should be open source and made available through a user-friendly web interface in a range of formats.
- **Awareness:** There is a need to raise awareness of available satellite SM products amongst potential users. Importantly, information is required on how users can access freely available satellite SM and which sensors and products are best for particular applications. This information should be provided in a format that can be easily understood by someone with limited knowledge of remote sensing.
- **Training:** Training opportunities in the use of satellite SM products are required. The user survey highlighted the huge demand for training workshops covering practical and theoretical aspects including: data access, data processing and software, understanding uncertainty, data assimilation and applications. Online training materials, such as online guides and webinars, would also be highly valuable to end users.
- **Product Characteristics:** Future advancements in sensors and retrieval methods will increase the usefulness of satellite SM products. In particular, the low spatial resolution of current satellite SM products is still a significant limitation for some applications. To help address this, downscaled products should be developed, with well characterised uncertainties, and made available to the user community.
- **Ground Data:** Increases in the availability and spatial coverage of ground-based SM observation are needed for the calibration and validation of satellite SM products. Low-cost sensor networks have potential as a means of improving availability of in situ SM data. A future study investigating this possibility in more depth would be highly valuable.
- **Collaboration:** A user community should be developed to encourage collaboration across disciplines for the application of satellite SM products. Knowledge sharing between the remote sensing and user communities should be encouraged to improve compatibility between satellite products and models. A future knowledge-transfer project, focusing on the use of satellite SM data for commercial applications or by public organisations would also be beneficial.

An accompanying State of the Science Brief summarizing the key thematic points arising from the Activity can be found at www.iukwc.org

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8. References

- Adams, J.R., McNairn, H., Berg, A.A. and Champagne, C., 2015. Evaluation of near-surface soil moisture data from an AAFC monitoring network in Manitoba, Canada: Implications for L-band satellite validation. *Journal of Hydrology*, 521, pp.582-592.
- Albergel, C., Dorigo, W., Balsamo, G., Muñoz-Sabater, J., de Rosnay, P., Isaksen, L., Brocca, L., de Jeu, R. and Wagner, W., 2013. Monitoring multi-decadal satellite earth observation of soil moisture products through land surface reanalyses. *Remote Sensing of Environment*, 138, pp.77-89.
- Al-Shrafany, D., Rico-Ramirez, M.A., Han, D. and Bray, M., 2014. Comparative assessment of soil moisture estimation from land surface model and satellite remote sensing based on catchment water balance. *Meteorological Applications*, 21(3), pp.521-534.
- Al-Yaari, A., Wigneron, J.P., Kerr, Y., Rodriguez-Fernandez, N., O'Neill, P.E., Jackson, T.J., De Lannoy, G.J.M., Al Bitar, A., Mialon, A., Richaume, P. and Walker, J.P., 2017. Evaluating soil moisture retrievals from ESA's SMOS and NASA's SMAP brightness temperature datasets. *Remote sensing of environment*, 193, pp.257-273.
- Al-Yaari, A., Wigneron, J.P., Ducharne, A., Kerr, Y.H., Wagner, W., De Lannoy, G., Reichle, R., Al Bitar, A., Dorigo, W., Richaume, P. and Mialon, A., 2014. Global-scale comparison of passive (SMOS) and active (ASCAT) satellite-based microwave soil moisture retrievals with soil moisture simulations (MERRA-Land). *Remote Sensing of Environment*, 152, pp.614-626.
- Anam, R., Chishtie, F., Ghuffar, S., Qazi, W. and Shahid, I., 2017. Inter-comparison of SMOS and AMSR-E soil moisture products during flood years (2010–2011) over Pakistan. *European Journal of Remote Sensing*, 50(1), pp.442-451.
- Barnwal, P. and Kotani, K., 2013. Climatic impacts across agricultural crop yield distributions: An application of quantile regression on rice crops in Andhra Pradesh, India. *Ecological Economics*, 87, pp.95-109.
- Beljaars, A.C., Viterbo, P., Miller, M.J. and Betts, A.K., 1996. The anomalous rainfall over the United States during July 1993: Sensitivity to land surface parameterization and soil moisture anomalies. *Monthly Weather Review*, 124(3), pp.362-383.
- Berwal, P., Murthy, C.S., Raju, P.V. and Sai, M.S., 2016. Geospatial analysis of near-surface soil moisture time series data over Indian region. *ISPRS-International archives of the photogrammetry, remote sensing and spatial information sciences*, pp.631-637.
- Brocca, L., Hasenauer, S., Lacava, T., Melone, F., Moramarco, T., Wagner, W., Dorigo, W., Matgen, P., Martínez-Fernández, J., Llorens, P. and Latron, J., 2011. Soil moisture estimation through ASCAT and AMSR-E sensors: An intercomparison and validation study across Europe. *Remote Sensing of Environment*, 115(12), pp.3390-3408.
- Brocca, L., Ciabatta, L., Massari, C., Moramarco, T., Hahn, S., Hasenauer, S., Kidd, R., Dorigo, W., Wagner, W. and Levizzani, V., 2014. Soil as a natural rain gauge: Estimating global rainfall from satellite soil moisture data. *Journal of Geophysical Research: Atmospheres*, 119(9), pp.5128-5141.
- Brocca, L., Ciabatta, L., Massari, C., Camici, S. and Tarpanelli, A., 2017a. Soil moisture for hydrological applications: Open questions and new opportunities. *Water*, 9(2), p.140.
- Brocca, L., Crow, W.T., Ciabatta, L., Massari, C., Rosnay, P.D., Enenkel, M., Hahn, S., Amarnath, G., Camici, S., Tarpanelli, A. and Wagner, W., 2017b. A review of the applications of ASCAT [Advanced SCATterometer] soil moisture products.
- Brocca, L., Ciabatta, L., Massari, C., Camici, S. and Tarpanelli, A., 2017c. Soil moisture for hydrological applications: Open questions and new opportunities. *Water*, 9(2), p.140. Capecchi,

- V. and Brocca, L., 2014. A simple assimilation method to ingest satellite soil moisture into a limited-area NWP model. *Meteorologische Zeitschrift*, 23, pp.105-121.
- Carlson, T., 2007. An overview of the "triangle method" for estimating surface evapotranspiration and soil moisture from satellite imagery. *Sensors*, 7(8), pp.1612-1629.
- Carrera, M.L., Bélair, S. and Bilodeau, B., 2015. The Canadian land data assimilation system (CaLDAS): Description and synthetic evaluation study. *Journal of Hydrometeorology*, 16(3), pp.1293-1314.
- CEH UK, 2017. The UK drought Portal - Near Real-Time Updates. Available at: <https://www.ceh.ac.uk/news-and-media/blogs/uk-drought-portal-near-real-time-updates>
- CEH UK, 2018. HYROD-Jules: Next Generation Land-Surface and Hydrological Predictions. Available at: <https://www.ceh.ac.uk/hydrojules>
- Champagne, C., Davidson, A., Cherneski, P., L'Heureux, J. and Hadwen, T., 2015. Monitoring agricultural risk in Canada using L-band passive microwave soil moisture from SMOS. *Journal of Hydrometeorology*, 16(1), pp.5-18.
- Champagne, C., Rowlandson, T., Berg, A., Burns, T., L'Heureux, J., Tetlock, E., Adams, J.R., McNairn, H., Toth, B. and Itenfsu, D., 2016. Satellite surface soil moisture from SMOS and Aquarius: Assessment for applications in agricultural landscapes. *International journal of applied earth observation and geoinformation*, 45, pp.143-154.
- Chakrabarti, S., Bongiovanni, T., Judge, J., Nagarajan, K. and Principe, J.C., 2015. Downscaling Satellite-Based Soil Moisture in Heterogeneous Regions Using High-Resolution Remote Sensing Products and Information Theory: A Synthetic Study. *IEEE Trans. Geoscience and Remote Sensing*, 53(1), pp.85-101.
- Chakraborty, A., Sai, M.S., Murthy, C.S., Roy, P.S. and Behera, G., 2012. Assessment of area favourable for crop sowing using AMSR-E derived Soil Moisture Index (AMSR-E SMI). *International Journal of Applied Earth Observation and Geoinformation*, 18, pp.537-547.
- Chakraborty, A., Chahar, B.R., Sharma, O.P. and Dhanya, C.T., 2016. A regional scale performance evaluation of SMOS and ESA-CCI soil moisture products over India with simulated soil moisture from MERRA-Land. *Remote Sensing of Environment*, 186, pp.514-527.
- Chattopadhyay, N. and Chandras, S., 2018. Agro-Meteorological Advisory Services for Informed Decision Making in India. In *Biodiversity and Climate Change Adaptation in Tropical Islands* (pp. 763-783).
- Chen, X., Su, Y., Liao, J., Shang, J., Dong, T., Wang, C., Liu, W., Zhou, G. and Liu, L., 2016. Detecting significant decreasing trends of land surface soil moisture in eastern China during the past three decades (1979–2010). *Journal of Geophysical Research: Atmospheres*, 121(10), pp.5177-5192.
- Crow, W.T., Berg, A.A., Cosh, M.H., Loew, A., Mohanty, B.P., Panciera, R., de Rosnay, P., Ryu, D. and Walker, J.P., 2012. Upscaling sparse ground-based soil moisture observations for the validation of coarse-resolution satellite soil moisture products. *Reviews of Geophysics*, 50(2).
- Das, H. and Singh, S.K., 2004. Useful byproducts from cellulosic wastes of agriculture and food industry- a critical appraisal. *Critical reviews in food science and nutrition*, 44(2), pp.77-89.
- Davies, T., Cullen, M.J., Malcolm, A.J., Mawson, M.H., Staniforth, A., White, A.A. and Wood, N., 2005. A new dynamical core for the Met Office's global and regional modelling of the atmosphere. *Quarterly Journal of the Royal Meteorological Society*, 131(608), pp.1759-1782.
- De Lannoy, G.J. and Reichle, R.H., 2016a. Global assimilation of multiangle and multipolarization SMOS brightness temperature observations into the GEOS-5 catchment land surface model for soil moisture estimation. *Journal of Hydrometeorology*, 17(2), pp.669-691.

- De Lannoy, G.J. and Reichle, R.H., 2016b. Assimilation of SMOS brightness temperatures or soil moisture retrievals into a land surface model. *Hydrology and Earth System Sciences*, 20(12), pp.4895-4911.
- De Rosnay, P., Drusch, M., Vasiljevic, D., Balsamo, G., Albergel, C. and Isaksen, L., 2013. A simplified Extended Kalman Filter for the global operational soil moisture analysis at ECMWF. *Quarterly Journal of the Royal Meteorological Society*, 139(674), pp.1199-1213.
- De Rosnay, P., Balsamo, G., Albergel, C., Muñoz-Sabater, J. and Isaksen, L., 2014. Initialisation of land surface variables for numerical weather prediction. *Surveys in Geophysics*, 35(3), pp.607-621.
- De Rosnay, P., Albergel, C., Balsamo, G. and Muñoz Sabater, J., 2012, April. ASCAT data assimilation at ECMWF. In *EGU General Assembly Conference Abstracts* (Vol. 14, p. 5488).
- Department for Environment, Food and Rural Affairs UK, 2015. Agriculture in the United Kingdom - 2014. Available at: https://assets.publishing.service.gov.uk/government/uploads/system/uploads/attachment_data/file/430411/auk-2014-28may15a.pdf
- Department for Environment, Food and Rural Affairs UK, 2010. June Census of Agriculture and horticulture (Land use and livestock on agricultural holdings at 1 June 2010) UK- Final Results. Available at: <http://webarchive.nationalarchives.gov.uk/20110911091657/http://www.defra.gov.uk/statistics/files/defra-stats-foodfarm-landusellivestock-june-statsrelease-uk-110525.pdf>
- Dirmeyer, P.A., 2000. Using a global soil wetness dataset to improve seasonal climate simulation. *Journal of Climate*, 13(16), pp.2900-2922.
- Dharssi, I., Bovis, K.J., Macpherson, B. and Jones, C.P., 2011. Operational assimilation of ASCAT surface soil wetness at the Met Office. *Hydrology and Earth System Sciences*, 15(8), pp.2729-2746.
- Dorigo, W.A., Wagner, W., Hohensinn, R., Hahn, S., Paulik, C., Xaver, A., Gruber, A., Drusch, M., Mecklenburg, S., Oevelen, P.V. and Robock, A., 2011. The International Soil Moisture Network: a data hosting facility for global in situ soil moisture measurements. *Hydrology and Earth System Sciences*, 15(5), pp.1675-1698.
- Dorigo, W.A., Xaver, A., Vreugdenhil, M., Gruber, A., Hegyiova, A., Sanchis-Dufau, A.D., Zamojski, D., Cordes, C., Wagner, W. and Drusch, M., 2013. Global automated quality control of in situ soil moisture data from the International Soil Moisture Network. *Vadose Zone Journal*, 12(3).
- Dorigo, W.A., Gruber, A., De Jeu, R.A.M., Wagner, W., Stacke, T., Loew, A., Albergel, C., Brocca, L., Chung, D., Parinussa, R.M. and Kidd, R., 2015. Evaluation of the ESA CCI soil moisture product using ground-based observations. *Remote Sensing of Environment*, 162, pp.380-395.
- Dorigo, W., Wagner, W., Albergel, C., Albrecht, F., Balsamo, G., Brocca, L., Chung, D., Ertl, M., Forkel, M., Gruber, A. and Haas, E., 2017. ESA CCI Soil Moisture for improved Earth system understanding: State-of-the art and future directions. *Remote Sensing of Environment*, 203, pp.185-215.
- Dumedah, G., Walker, J.P. and Chik, L., 2014. Assessing artificial neural networks and statistical methods for infilling missing soil moisture records. *Journal of Hydrology*, 515, pp.330-344.
- Dumedah, G. and Walker, J.P., 2017. Assessment of model behavior and acceptable forcing data uncertainty in the context of land surface soil moisture estimation. *Advances in water resources*, 101, pp.23-36.
- El Sharif, H., Wang, J. and Georgakakos, A.P., 2015. Modeling regional crop yield and irrigation demand using SMAP type of soil moisture data. *Journal of Hydrometeorology*, 16(2), pp.904-916.
- ESA CCI Soil Moisture website (2018). [online] Available at: <https://www.esa-soilmoisture-cci.org/node/93> [Accessed 31 Oct. 2018].

- Escobar, V.M., Srinivasan, M. and Arias, S.D., 2016. Improving NASA's Earth observation systems and data programs through the engagement of mission early adopters. In *Earth Science Satellite Applications* (pp. 223-267). Springer, Cham.
- Fang, L., Hain, C.R., Zhan, X. and Anderson, M.C., 2016. An inter-comparison of soil moisture data products from satellite remote sensing and a land surface model. *International journal of applied earth observation and geoinformation*, 48, pp.37-50.
- Fisher, D.K. and Gould, P.J., 2012. Open-source hardware is a low-cost alternative for scientific instrumentation and research. *Modern Instrumentation*, 1(02), p.8.
- Foley, J.A., Ramankutty, N., Brauman, K.A., Cassidy, E.S., Gerber, J.S., Johnston, M., Mueller, N.D., O'Connell, C., Ray, D.K., West, P.C. and Balzer, C., 2011. Solutions for a cultivated planet. *Nature*, 478(7369), p.337.
- Food and Agriculture Organization of the United Nations, 2017. Rice Market Monitor:October 2017.
- González-Zamora, Á., Sánchez, N., Martínez-Fernández, J., Gumuzzio, Á., Piles, M. and Olmedo, E., 2015. Long-term SMOS soil moisture products: A comprehensive evaluation across scales and methods in the Duero Basin (Spain). *Physics and Chemistry of the Earth, Parts A/B/C*, 83, pp.123-136.
- GOV.UK. (2004). Future of flood and coastal defence. [online] Available at: <https://www.gov.uk/government/collections/flood-and-coastal-defence> [Accessed 31 Oct. 2018].
- Gruber, A., Su, C.H., Crow, W.T., Zwieback, S., Dorigo, W.A. and Wagner, W., 2016a. Estimating error cross-correlations in soil moisture data sets using extended collocation analysis. *Journal of Geophysical Research: Atmospheres*, 121(3), pp.1208-1219. - GRUBER 2016 A
- Gruber, A., Su, C.H., Zwieback, S., Crow, W., Dorigo, W. and Wagner, W., 2016b. Recent advances in (soil moisture) triple collocation analysis. *International Journal of Applied Earth Observation and Geoinformation*, 45, pp.200-211.
- Gruber, A., Dorigo, W.A., Zwieback, S., Xaver, A. and Wagner, W., 2013. Characterizing coarse-scale representativeness of in situ soil moisture measurements from the International Soil Moisture Network. *Vadose Zone Journal*, 12(2).
- Gupta, M., Srivastava, P.K. and Islam, T., 2016. Integrative Use of Near-Surface Satellite Soil Moisture and Precipitation for Estimation of Improved Irrigation Scheduling Parameters. In *Satellite Soil Moisture Retrieval* (pp. 271-288).
- Hannaford, J. and Marsh, T.J., 2008. High-flow and flood trends in a network of undisturbed catchments in the UK. *International Journal of Climatology: A Journal of the Royal Meteorological Society*, 28(10), pp.1325-1338.
- Ines, A.V., Das, N.N., Hansen, J.W. and Njoku, E.G., 2013. Assimilation of remotely sensed soil moisture and vegetation with a crop simulation model for maize yield prediction. *Remote Sensing of Environment*, 138, pp.149-164.
- Jayakumar, M., Rajavel, M. and Surendran, U., 2016. Climate-based statistical regression models for crop yield forecasting of coffee in humid tropical Kerala, India. *International journal of biometeorology*, 60(12), pp.1943-1952.
- Karthikeyan, L., Pan, M., Wanders, N., Kumar, D.N. and Wood, E.F., 2017. Four decades of microwave satellite soil moisture observations: Part 1. A review of retrieval algorithms. *Advances in Water Resources*, 109, pp.106-120.
- Kendon, M., Marsh, T. and Parry, S., 2013. The 2010–2012 drought in England and Wales. *Weather*, 68(4), pp.88-95.

- Kerr, Y.H., Al-Yaari, A., Rodriguez-Fernandez, N., Parrens, M., Molero, B., Leroux, D., Bircher, S., Mahmoodi, A., Mialon, A., Richaume, P. and Delwart, S., 2016. Overview of SMOS performance in terms of global soil moisture monitoring after six years in operation. *Remote Sensing of Environment*, 180, pp.40-63.
- Kim, J. and Hogue, T.S., 2012. Improving spatial soil moisture representation through integration of AMSR-E and MODIS products. *IEEE Transactions on Geoscience and Remote Sensing*, 50(2), pp.446-460.
- Koster, R.D., Sud, Y.C., Guo, Z., Dirmeyer, P.A., Bonan, G., Oleson, K.W., Chan, E., Versegny, D., Cox, P., Davies, H. and Kowalczyk, E., 2006. GLACE: the global land-atmosphere coupling experiment. Part I: overview. *Journal of Hydrometeorology*, 7(4), pp.590-610.
- Koster, R.D., Dirmeyer, P.A., Guo, Z., Bonan, G., Chan, E., Cox, P., Gordon, C.T., Kanae, S., Kowalczyk, E., Lawrence, D. and Liu, P., 2004. Regions of strong coupling between soil moisture and precipitation. *Science*, 305(5687), pp.1138-1140.
- Koster, R.D., Suarez, M.J., Higgins, R.W. and Van den Dool, H.M., 2003. Observational evidence that soil moisture variations affect precipitation. *Geophysical Research Letters*, 30(5).
- Kumar, S.V., Peters-Lidard, C.D., Santanello, J.A., Reichle, R.H., Draper, C.S., Koster, R.D., Nearing, G. and Jasinski, M.F., 2015. Evaluating the utility of satellite soil moisture retrievals over irrigated areas and the ability of land data assimilation methods to correct for unmodeled processes. *Hydrology and Earth System Sciences*, 19(11), pp.4463-4478.
- Lawston, P.M., Santanello, J.A. and Kumar, S.V., 2017. Irrigation signals detected from SMAP soil moisture retrievals. *Geophysical Research Letters*, 44(23).
- Leroux, D.J., Kerr, Y.H., Richaume, P. and Fieuzal, R., 2013. Spatial distribution and possible sources of SMOS errors at the global scale. *Remote Sensing of Environment*, 133, pp.240-250.
- Lievens, H., De Lannoy, G.J.M., Al Bitar, A., Drusch, M., Dumedah, G., Franssen, H.J.H., Kerr, Y.H., Tomer, S.K., Martens, B., Merlin, O. and Pan, M., 2016. Assimilation of SMOS soil moisture and brightness temperature products into a land surface model. *Remote sensing of environment*, 180, pp.292-304.
- Lei, F., Crow, W.T., Shen, H., Su, C.H., Holmes, T.R., Parinussa, R.M. and Wang, G., 2018. Assessment of the impact of spatial heterogeneity on microwave satellite soil moisture periodic error. *Remote Sensing of Environment*, 205, pp.85-99.
- Levine, P.A., Randerson, J.T., Swenson, S.C. and Lawrence, D.M., 2016. Evaluating the strength of the land-atmosphere moisture feedback in Earth system models using satellite observations. *Hydrology and Earth System Sciences (Online)*, 20(12).
- Massari, C., Camici, S., Ciabatta, L. and Brocca, L., 2018. Exploiting satellite-based surface soil moisture for flood forecasting in the Mediterranean area: state update versus rainfall correction. *Remote Sensing*, 10(2), p.292.
- Mason, D., Garcia-Pintado, J., Cloke, H. and Dance, S., 2017, April. Assimilating high resolution remotely sensed soil moisture into a distributed hydrologic model to improve runoff prediction: a case study. In *EGU General Assembly Conference Abstracts* (Vol. 19, p. 4504).
- McColl, K.A., Vogelzang, J., Konings, A.G., Entekhabi, D., Piles, M. and Stoffelen, A., 2014. Extended triple collocation: Estimating errors and correlation coefficients with respect to an unknown target. *Geophysical Research Letters*, 41(17), pp.6229-6236.
- McNally, A., Husak, G.J., Brown, M., Carroll, M., Funk, C., Yattheendradas, S., Arsenault, K., Peters-Lidard, C. and Verdin, J.P., 2015. Calculating crop water requirement satisfaction in the West Africa Sahel with remotely sensed soil moisture. *Journal of Hydrometeorology*, 16(1), pp.295-305.

- Miralles, D.G., Van Den Berg, M.J., Teuling, A.J. and De Jeu, R.A.M., 2012. Soil moisture temperature coupling: A multiscale observational analysis. *Geophysical Research Letters*, 39(21).
- Moran, M.S., Doorn, B., Escobar, V. and Brown, M.E., 2015. Connecting NASA science and engineering with earth science applications. *Journal of Hydrometeorology*, 16(1), pp.473-483.
- Mohanty, B.P., Cosh, M.H., Lakshmi, V. and Montzka, C., 2017. Soil moisture remote sensing: State-of-the-science. *Vadose Zone Journal*, 16(1).
- Montzka, C., Rötzer, K., Bogen, H.R., Sanchez, N. and Vereecken, H., 2018. A New Soil Moisture Downscaling Approach for SMAP, SMOS, and ASCAT by Predicting Sub-Grid Variability. *Remote Sensing*, 10(3), p.427.
- Muñoz-Sabater, J., Al Bitar, A. and Brocca, L., 2016. Soil moisture retrievals based on active and passive microwave data: State-of-the-art and operational applications. In *Satellite Soil Moisture Retrieval* (pp. 351-378).
- Muñoz-Sabater, J., 2015. Incorporation of passive microwave brightness temperatures in the ECMWF soil moisture analysis. *Remote Sensing*, 7(5), pp.5758-5784.
- National River Flow Archives, 2018. Major Hydrological Events UK. Accessed from: <https://nrfa.ceh.ac.uk/occasional-reports>
- Nicolai-Shaw, N., Zscheischler, J., Hirschi, M., Gudmundsson, L. and Seneviratne, S.I., 2017. A drought event composite analysis using satellite remote-sensing based soil moisture. *Remote Sensing of Environment*, 203, pp.216-225.
- Nicolai-Shaw, N., Gudmundsson, L., Hirschi, M. and Seneviratne, S.I., 2016. Long-term predictability of soil moisture dynamics at the global scale: Persistence versus large-scale drivers. *Geophysical Research Letters*, 43(16), pp.8554-8562.
- Notaro, M., 2008. Statistical identification of global hot spots in soil moisture feedbacks among IPCC AR4 models. *Journal of Geophysical Research: Atmospheres*, 113(D9).
- O'Brien, K., Leichenko, R., Kelkar, U., Venema, H., Aandahl, G., Tompkins, H., Javed, A., Bhadwal, S., Barg, S., Nygaard, L. and West, J., 2004. Mapping vulnerability to multiple stressors: climate change and globalization in India. *Global environmental change*, 14(4), pp.303-313.
- Padhee, S.K., Nikam, B.R., Dutta, S. and Aggarwal, S.P., 2017. Using satellite-based soil moisture to detect and monitor spatiotemporal traces of agricultural drought over Bundelkhand region of India. *GIScience & Remote Sensing*, 54(2), pp.144-166.
- Parihar, J.S. and Oza, M.P., 2006, December. FASAL: an integrated approach for crop assessment and production forecasting. In *Agriculture and Hydrology Applications of Remote Sensing* (Vol. 6411, p. 641101). International Society for Optics and Photonics.
- Parihar, J.S., 2016. FASAL concept in meeting the requirements of assessment and forecasting crop production affected by extreme weather events. *MAUSAM*, 67(1), pp.93-104.
- Parry, S., Marsh, T. and Kendon, M., 2013. 2012: from drought to floods in England and Wales. *Weather*, 68(10), pp.268-274.
- Paulik, C., Dorigo, W., Wagner, W. and Kidd, R., 2014. Validation of the ASCAT Soil Water Index using in situ data from the International Soil Moisture Network. *International journal of applied earth observation and geoinformation*, 30, pp.1-8.
- Peng, J., Loew, A., Merlin, O. and Verhoest, N.E., 2017. A review of spatial downscaling of satellite remotely sensed soil moisture. *Reviews of Geophysics*, 55(2), pp.341-366.

- Petropoulos, G.P., Ireland, G. and Barrett, B., 2015. Surface soil moisture retrievals from remote sensing: Current status, products & future trends. *Physics and Chemistry of the Earth, Parts A/B/C*, 83, pp.36-56.
- Petropoulos, G.P., Srivastava, P.K., Piles, M. and Pearson, S., 2018. Earth observation-based operational estimation of soil moisture and evapotranspiration for agricultural crops in support of sustainable water management. *Sustainability*, 10(1), p.181.
- Piles, M. and Sánchez, N., 2016. Spatial downscaling of passive microwave data with visible-to-infrared information for high-resolution soil moisture mapping. In *Satellite Soil Moisture Retrieval* (pp. 109-132).
- Quaife, T.L., Black, E., Browne, P. and Lewis, J., 2015, December. Assimilating ESA-CCI Soil Moisture into the JULES-EMPIRE Data Assimilation System. In *AGU Fall Meeting Abstracts*.
- Rao, S.S., Sahadevan, D.K., Wadodkar, M.R., Chattaraj, S., Joseph, W., Rajankar, P., Sengupta, T., Venugopalan, M.V., Das, S.N., Joshi, A.K. and Sharma, J.R., 2016. Performance of global soil moisture products in crop growing region of Central India. *Journal of the Indian Society of Remote Sensing*, 44(2), pp.277-285.
- Rajak, D.R., Jain, R.K. and Ray, S.S., 2016. Early estimation of crop sown area by integrating multi-source data. *Journal of Geomatics*, 10(1).
- Ramsbottom, D., Sayers, P. and Panzeri, M., 2012. Climate Change Risk Assessment for the Floods and Coastal Erosion Sector. *UK 2012: Climate Change Risk Assessment*.
- Reichle, R.H., Crow, W.T. and Keppenne, C.L., 2008. An adaptive ensemble Kalman filter for soil moisture data assimilation. *Water resources research*, 44(3).
- Ridler, M.E., Madsen, H., Stisen, S., Bircher, S. and Fensholt, R., 2014. Assimilation of SMOS-derived soil moisture in a fully integrated hydrological and soil-vegetation-atmosphere transfer model in Western Denmark. *Water Resources Research*, 50(11), pp.8962-8981.
- Rey, D., Holman, I.P., Daccache, A., Morris, J., Weatherhead, E.K. and Knox, J.W., 2016. Modelling and mapping the economic value of supplemental irrigation in a humid climate. *Agricultural Water Management*, 173, pp.13-22.
- Sakai, T., Izumi, T., Okada, M., Nishimori, M., Grünwald, T., Prueger, J., Cescatti, A., Korres, W., Schmidt, M., Carrara, A. and Loubet, B., 2016. Varying applicability of four different satellite-derived soil moisture products to global gridded crop model evaluation. *International journal of applied earth observation and geoinformation*, 48, pp.51-60.
- Scipal, K., Drusch, M. and Wagner, W., 2008. Assimilation of a ERS scatterometer derived soil moisture index in the ECMWF numerical weather prediction system. *Advances in water resources*, 31(8), pp.1101-1112.
- Seneviratne, S.I., Corti, T., Davin, E.L., Hirschi, M., Jaeger, E.B., Lehner, I., Orlowsky, B. and Teuling, A.J., 2010. Investigating soil moisture-climate interactions in a changing climate: A review. *Earth-Science Reviews*, 99(3-4), pp.125-161.
- Sesha Sai, M.S., Murthy, C.S., Chandrasekar, K., Jeyaseelan, A.T., Diwakar, P.G. and Dadhwal, V.K., 2016. Agricultural drought: Assessment & monitoring. *MAUSAM*, 67(1), pp.131-142.
- Singh, G., Das, N.N., Panda, R.K., Mohanty, B., Entekhabi, D. and Bhattacharya, B.K., 2016, December. High-Resolution Soil Moisture Retrieval using SMAP-L Band Radiometer and RISAT-C band Radar Data for the Indian Subcontinent. In *AGU Fall Meeting Abstracts*.
- Singh, D., Gupta, P.K., Pradhan, R., Dubey, A.K. and Singh, R.P., 2017. Discerning shifting irrigation practices from passive microwave radiometry over Punjab and Haryana. *Journal of Water and Climate Change*, 8(2), pp.303-319.

- Srivastava, P.K., Han, D., Ramirez, M.R. and Islam, T., 2013. Machine learning techniques for downscaling SMOS satellite soil moisture using MODIS land surface temperature for hydrological application. *Water resources management*, 27(8), pp.3127-3144.
- Taylor, C.M., de Jeu, R.A., Guichard, F., Harris, P.P. and Dorigo, W.A., 2012. Afternoon rain more likely over drier soils. *Nature*, 489(7416), p.423.
- Tebbs, E., Gerard, F., Petrie, A. and De Witte, E., 2016. Emerging and potential future applications of satellite-based soil moisture products. In *Satellite Soil Moisture Retrieval* (pp. 379-400).
- Thakur, P.K., Aggarwal, S.P., Shamra, V.C., Nikam, B.R., Garg, V., Chouksey, A., Dhote, P. and Singh, C. (2015). Flood early warning system for North West Himalaya using integration of weather forecasting, hydrological and hydrodynamic models. Abstract accepted and published in ISPRS WG VIII/1 Workshop on Geospatial Technology for Disaster Risk Reduction, Jaipur, India on December 17, 2015
- Thiruvengadam, P. and Rao, Y.S., 2016, July. Spatio-temporal variation of soil moisture and drought monitoring using passive microwave remote sensing. In *Geoscience and Remote Sensing Symposium (IGARSS), 2016 IEEE International* (pp. 3126-3129). IEEE.
- Tuttle, S. and Salvucci, G., 2016. Empirical evidence of contrasting soil moisture–precipitation feedbacks across the United States. *Science*, 352(6287), pp.825-828.
- Tripathi, A., Mishra, A.K. and Verma, G., 2016. Impact of preservation of subsoil water act on groundwater depletion: the case of Punjab, India. *Environmental management*, 58(1), pp.48-59.
- Venkatasubramanian, K., Tall, A., Hansen, J. and Aggarwal, P.K., 2014. Assessment of India's Agrometeorological Advisory Service from a farmer perspective.
- Vuolo, F., D'Urso, G., De Michele, C., Bianchi, B. and Cutting, M., 2015. Satellite-based irrigation advisory services: A common tool for different experiences from Europe to Australia. *Agricultural water management*, 147, pp.82-95.
- Wagner, W., Hahn, S., Figa, J., Albergel, C., de Rosnay, P., Brocca, L., de Jeu, R., Hasenauer, S. and Dorigo, W., 2013a. Operations, challenges, and prospects of satellite-based surface soil moisture data services. In *Remote Sensing of Energy Fluxes and Soil Moisture Content*. (pp. 463-488).
- Wagner, W., Hahn, S., Kidd, R., Melzer, T., Bartalis, Z., Hasenauer, S., Figa-Saldaña, J., de Rosnay, P., Jann, A., Schneider, S. and Komma, J., 2013b. The ASCAT soil moisture product: A review of its specifications, validation results, and emerging applications. *Meteorologische Zeitschrift*, 22(1), pp.5-33.
- Wagner, W., Blochl, G., Pampaloni, P., Calvet, J.C., Bizzarri, B., Wigneron, J.P. and Kerr, Y., 2007b. Operational readiness of microwave remote sensing of soil moisture for hydrologic applications. *Nordic hydrology*, 38(1), pp.1-20.
- Wagner, W., Naeimi, V., Scipal, K., de Jeu, R. and Martínez-Fernández, J., 2007a. Soil moisture from operational meteorological satellites. *Hydrogeology Journal*, 15(1), pp.121-131.
- Wanders, N., Karssenbergh, D., Bierkens, M., Parinussa, R., de Jeu, R., van Dam, J. and de Jong, S., 2012. Observation uncertainty of satellite soil moisture products determined with physically-based modelling. *Remote Sensing of Environment*, 127, pp.341-356.
- Wigneron, J.P., Jackson, T.J., O'Neill, P., De Lannoy, G., De Rosnay, P., Walker, J.P., Ferrazzoli, P., Mironov, V., Bircher, S., Grant, J.P. and Kurum, M., 2017. Modelling the passive microwave signature from land surfaces: A review of recent results and application to the L-band SMOS & SMAP soil moisture retrieval algorithms. *Remote Sensing of Environment*, 192, pp.238-262.
- Wu, Q., Liu, H., Wang, L. and Deng, C., 2016. Evaluation of AMSR2 soil moisture products over the contiguous United States using in situ data from the International Soil Moisture Network. *International journal of applied earth observation and geoinformation*, 45, pp.187-199.

Yang, Z., Shrestha, R., Crow, W., Bolten, J., Mladenova, I., Yu, G. and Di, L., 2016, July. Evaluation of assimilated SMOS Soil Moisture data for US cropland Soil Moisture monitoring. In *Geoscience and Remote Sensing Symposium (IGARSS), 2016 IEEE International* (pp. 5244-5247). IEEE.

Yuan, S. and Quiring, S.M., 2017. Evaluation of soil moisture in CMIP5 simulations over the contiguous United States using in situ and satellite observations. *Hydrology and Earth System Sciences*, 21(4), p.2203.

Zhan, X., Zheng, W., Fang, L., Liu, J., Hain, C., Yin, J. and Ek, M., 2016, July. A preliminary assessment of the impact of SMAP Soil Moisture on numerical weather Forecasts from GFS and NUWRF models. In *Geoscience and Remote Sensing Symposium (IGARSS), 2016 IEEE International* (pp. 5229-5232). IEEE.

Zhao, W. and Li, A., 2013. A downscaling method for improving the spatial resolution of AMSR-E derived soil moisture product based on MSG-SEVIRI data. *Remote Sensing*, 5(12), pp.6790-6811.

Zreda, M., Desilets, D., Ferré, T.P.A. and Scott, R.L., 2008. Measuring soil moisture content non-invasively at intermediate spatial scale using cosmic-ray neutrons. *Geophysical Research Letters*, 35(21).



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